Fragmentation-aware spectrum assignment strategies for elastic optical networks with static operation.

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***Abstract*—One of the main problems in the design of elastic optical networks is the Routing, Modulation-Level, and Spectrum Assignment problem (RMLSA). In this work, we propose new strategies to solve the spectrum assignment (SA) sub-problem for EONs architectures with static network operation. To this end, we developed two new approaches called Sliding-Fit (SF) and Parcel-Fit (PF), focused on minimizing the spectrum fragmentation obtained when attending network demands. These strategies change to standard paradigm use to search an amount of consecutive FSUs for a given user by choosing a subset of FSUs in the frequency spectrum and later finding users for the selected FSUs. Additionally, the method relies on a physical-layer impairment (PLI) model to compute the maximum optical reach and bandwidth demands based on the modulation level - bitrate pair.**

Experimental results showed that the proposed algorithms obtain less spectrum fragmentation than the best found in the literature, allowing to assign a higher number of users, decreasing the network capacity or increasing the efficiency in the use of resources.

***Index Terms*—Elastic Optical Networks, Routing, Modulation Level, Spectrum Assignment**

I. Introduction

Nowadays, the majority of internet traffic is transmitted over optical networks. Since WDM (Wavelength Division Multiplexing) networks provide high bandwidth and transmission rates, they can satisfy current internet traffic demands. However, with the exponential growth of annual traffic (around 30% [1], [2]), the capacity of these networks is expected to be insufficient. This situation, called "Capacity Crunch", manifests an impending inability of current optical architectures to support future bandwidth demands [3]–[5].

There are two possible paths to face this problem. The first one is to increase the current infrastructure, installing as much fiber as it is needed. Although this option increases the number of network resources, it requires significant investments. This investment cannot be avoided, but it should be postponed as long as possible. Another alternative is to manage network resources efficiently. This second alternative has been an important focus of researchers [2]. WDM networks are inefficient due to the spectrum grid's coarse granularity, typically of 50 GHz by channel, according to the International Telecommunications Union (ITU) standard [6]. This situation implies that regardless of the user's bandwidth needs, the entire channel will be reserved.

A new architecture paradigm, called Elastic Optical Networks (EON), has been proposed to face prior problems [2], [7]. EON aims to allocate resources according to the bandwidth requirements of the user. In EONs, each channel is divided into narrow bands called Frequency Slot Unit (FSU), typically of 12.5 GHz. This way, different FSUs can be group flexibly to satisfy the users' needs. As a result, efficient management of the spectrum is achieved [2], [8], [9].

One of the main problems in designing EON is known as Routing and Spectrum Assignment (RSA). The RSA problem involves finding a route and a certain amount of available FSUs for the network user. Due to technical limitations, the RSA problem is subject to continuity and contiguity constraints. The continuity constraint refers to the fact that the assigned FSUs to a given connection must be maintained on their entire routes. On the other hand, when connections demand more than one FSU to transmit, they must be consecutive (contiguous) in the frequency spectrum. In wide-area networks, fiber optic communication systems are profoundly affected by the physical layer impairments (PLI) accumulated during propagation. In this context, the RSA problem becomes more difficult since we must ensure a minimum quality of transmission (QoT) for each connection request. A complex spectrum modulation format demands less FSU than simpler modulation formats, but with a much shorter optical reach (in kilometers). Therefore, choosing a modulation format is also important since we must consider the maximum distance to achieve a predefined quality of transmission. Consequently, all the tasks together are called routing, modulation level, and spectrum assignment (RMLSA) problem [10]–[12].

As a consequence of any solution to the RMLSA problem, some unused FSUs may appear among those assigned. This problem, known as spectrum fragmentation, can lead to a waste of bandwidth and produce unwanted results. Several heuristic algorithms have been proposed to solve the RMLSA problem focusing on minimizing the spectrum fragmentation [12]–[16]. They commonly focus on solving the routing sub-problem, while others face the spectrum assignment sub-

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problem. Some researchers [2], [17] remark that arranging the users, previous the spectrum assignment, significantly impacts the network performance. Nevertheless, as pointed out by [17], it is not enough. Therefore, more elaborate techniques are needed to reduce the spectrum fragmentation as much as possible.

This work aims to propose different spectrum assignment (SA) strategies to allocate the frequency slots in elastic optical network architectures. To this end, we developed two heuristic approaches to solve the RMLSA problem in mesh topologies with static network operation. These strategies focus on minimizing the spectrum fragmentation by developing a new spectrum assignment paradigm, searching users for a given subset of the frequency spectrum, instead of standard SA approaches. We also rely on a physical impairment model to compute the maximum reach of a given modulation format and bitrate of a user.

The remaining structure of this document is as follows: In Section II, we summarize the main strategies to solve the RMLSA problem found in the literature. Next, we present our proposals in Section III. In Section IV, we illustrate simulation examples, comparing them with the ones found in the literature. Finally, in Section V, we present some concluding remarks of this work.

II. State of Art

EONs have been considered as a promising candidate to support future Internet cost-efficiently. To this end, it is necessary to resolve the RMLSA problem correctly. Several different strategies can solve this problem. These strategies are grouped into two categories: Optimization and Ad-hoc solutions.

Optimization methods try to solve the RMLSA problem by minimizing the network's capacity. Several optimization techniques proposed in the literature make use of linear programming (ILP) models [16]. However, the extensive amount of variables and a large number of constraints make these models be a time-consuming task even for small networks. For this reason, optimization models present scalability difficulties and the inability to solve the problem in a reasonable time. For instance, in [18], the authors proposed a pure ILP model for ring network topologies. This strategy presents scalability limits since they can only obtain results until 8 nodes ring topologies.

Theoretical analysis shows that routing and resource allocation belongs to the Nondeterministic Polynomial Complete (NP-C) problem [19]. Since there doesn't exist a polynomial-time algorithm for routing and resource allocation, a feasible strategy is to find near-optimal solutions by any means available. RMLSA ad-hoc solutions allow us to obtain time-efficiently solutions with real network topologies scalability. To this end, some heuristic strategies focus on solving the routing sub-problem, while others face the spectrum allocation. Typical solutions to the routing sub-problem are solved using the shortest routes [13], [20]–[22].

According to [9], the spectrum allocation techniques found in the literature are First-Fit (FF), Most-Used (MU), Best-Fit (BF), among several variations [21]. However, most approaches use the First-Fit scheme [16], [21]. In a First-Fit strategy, a subset of consecutive FSUs is considered available if the corresponding FSUs on each link of the user route are available. This way, we ensure continuity and contiguity constraints. Then the search for available slots starts from the first FSU in the link sequence. A request is accepted and assigned on each link belonging to the route if the complete demand is available. Otherwise, the request is rejected, and the network cannot serve the user. [21], [22].

III. Proposed Methods

In this section, we present a heuristic strategy to solve the RMLSA problem in EONs with static network operation. First, we introduce the physical-layer impairments model to obtain the bandwidth demands based on the bitrate demands - modulation format pair. Later, we present the definitions and procedures needed to solve the RMLSA problem. In the end, we describe our RMLSA strategy, illustrating the two new heuristic proposal for the spectrum assignment problem.

A. Physical layer impairments model

The quality of transmission (QoT) of optical communications depends on the accumulation of physical impairments, such as attenuation, ASE noise, dispersion, and non-linear impairments. The effect of optical reach and modulation format used is significant on solving the RMLSA. A significant number of bits per symbol increases the transmission sensitivity to degradation, making the transmission reach shorter for highly efficient modulation formats [23]. To consider this *path length - modulation level* constraint, the most common approach is to associate any modulation format available on the transponder with its maximum transmission reach. [9]. The modulation formats used in this work are binary phase-shift keying (BPSK), quadrature phase-shift keying (QPSK), and Λ-quadrature amplitude modulation (Λ-QAM), where Λ takes values 8, 16, 32, and 64. Table I is based on [24] and shows the transmission reach, using single-polarization, as a function of the modulation format and bitrates available at the transponders.

B. Definitions and sub-procedures needed

The network topology is represented by the graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ is the set of network nodes, and $\mathcal{L}$ is the set of unidirectional links. The set of users $\mathcal{U}$ contains all source-destination node pairs on the graph $\mathcal{G}$ demanding communication. Here we specify each user $u \in \mathcal{U}$ as $u = (\mathcal{S}_u, \mathcal{D}_u, \mathcal{F}_u, i_u)$, where parameters $\mathcal{S}_u, \mathcal{D}_u, \mathcal{F}_u$ and i_u represent the user's source node, the destination node, the FSU demands, and the initial FSU where the user demands are allocated, respectively. We use $i_u = 0$ to indicate that the user demand u has not been served. Consequently, by default, all users start with i_u equal to 0.

TABLE I
SPECTRUM REQUIREMENTS IN TERMS OF FSUS AND MAXIMUM ACHIEVABLE REACH (MAR) FOR EACH BIT-RATE AND MODULATION FORMAT PAIR.

Modulation Format	Bit Rate (Gbps)					MAR (km)
	10	40	100	400	1000	
BPSK	1	4	8	32	80	4000
QPSK	1	2	4	16	40	2000
8-QAM	1	2	3	11	27	1000
16-QAM	1	1	2	8	20	500
32-QAM	1	1	2	7	16	250
64-QAM	1	1	2	6	14	125

Algorithm 1 Fit sub-procedure

1: **procedure** FIT($\mathcal{F}_u$,r_u,s_1,s_2)
2: **for** $s := s_1$ to $s_2 - \mathcal{F}_u + 1$ **do**
3: **if** FSUs from s to $s + \mathcal{F}_u - 1$ in r_u are free **then**
4: Assign the FSUs to r_u
5: break;
6: **else if** $s := s_2 - \mathcal{F}_u + 1$ **then**
7: $s := 0$;
8: **return** s

Let $\mathcal{C} = \{c_\ell | \forall \ell \in \mathcal{L}\}$ be the set of capacities of each network link, in which c_ℓ is the number of FSUs of the link $\ell \in \mathcal{L}$. Let $\mathcal{R} = \{r_u | \forall u \in \mathcal{U}\}$ be the set of paths computed for all network users, where r_u is the route selected to user $u \in \mathcal{U}$, and $\|r_u\|$ is its route length, measured as the number of links. Finally, let $\mathcal{M} = \{\mu_u | \forall u \in \mathcal{U}\}$ be the set of modulation formats computed for all network users, in which μ_u is the modulation format chosen for user u to transmit along the route r_u.

Let us define, next, a sub-procedure needed for our proposal. We called it the "Fit" procedure, and its pseudo-code is illustrated in Algorithm 1. This function searches, for a given user a subset of available and consecutive FSUs on the links belonging to the user route, in a specific portion of the frequency spectrum.

Therefore, the inputs of the Fit procedure are $\mathcal{F}_u$, r_u, s_1 and s_2. The first two are the user u FSU demands and path, respectively. On the other hand, s_1 and s_2 refer to the first and last FSUs in which the search for available FSU takes place. Then, from **line 2 to 7**, the method iterates for all possible consecutive FSUs on the given portion limited by s_1 and s_2, searching for available FSU to the user u. If there are available FSUs in r_u, complying with the continuity and contiguity constraints, we assign the user's demand on all the links of its route (**line 4**), to finally return the first of the assigned FSUs in **line 8**. Otherwise, if the user's demand could not be assigned (**lines 6 to 7**), we return the value 0.

In algorithmic form, we symbolically write the previously explained procedure as s := Fit($\mathcal{F}_u, r_u, s_1, s_2$), obtaining the first slot in which user u is assigned.

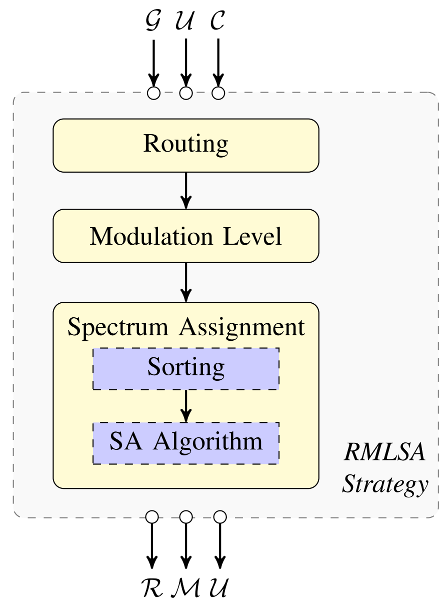


Fig. 1. Diagram showing the inputs required to run our proposal, the necessary steps to perform the method, and the outputs delivered

C. RMLSA Strategy

Solving the RMLSA problem is a process that involves three stages: the Routing stage, the Modulation-Level stage, and the Spectrum Assignment stage. The RMLSA strategy illustrated in Fig. 1 shows these stages to fulfill the RMLSA method. The inputs are the graph $\mathcal{G}$, the set of users $\mathcal{U}$, and the set of links' capacities $\mathcal{C}$.

First, the Routing stage computes all users' paths using any method available in the literature. In this work, we compute the shortest path for all network users with the commonly known Dijkstra algorithm.

Then, in the Modulation-Level Stage, we chose a modulation format according to the users' bitrate demands and corresponding route lengths. To translate the bitrate demands to spectrum requirements, Table I illustrates the spectrum requirements in terms of the number of FSU for each bitrate, reach, and modulation format. The modulation format considers a bit-error-rate (BER) threshold of 10^{-9} for each communication request. Then, the idea of this stage is to choose the more complex modulation format possible while complying with the maximum achievable reach on their path.

Finally, in the SA stage, the method assigns each user's bandwidth demands on the users' path links.

Once the previous process is finished, the method's outputs are the set of paths $\mathcal{R}$, the set of modulation format $\mathcal{M}$ decided for the users, and the updated set of users $\mathcal{U}$ with the FSUs assignments.

Next, we approach the spectrum assignment (SA) stage. In this stage, we first sort the users and assign the FSUs to each one of them, focusing on minimizing the spectrum fragmentation. Next, we describe the importance of sorting and

Algorithm 2 Sliding-Fit

1: **procedure** SLIDING-FIT($\mathcal{U}, \mathcal{R}$, "order", c, m)
2: $\quad \hat{\mathcal{U}} :=$ Sort($\mathcal{U}, \mathcal{R}$, "order")
3: $\quad$ **for** $fsu := 1$ to $c - m + 1$ **do**
4: $\quad\quad$ **for** all $u \in \hat{\mathcal{U}}$ **do**
5: $\quad\quad\quad i_u :=$Fit($\mathcal{F}_u, r_u, fsu, fsu + m - 1$)
6: $\quad\quad\quad$ **if** $i_u \neq 0$ **then**
7: $\quad\quad\quad\quad \hat{\mathcal{U}} := \hat{\mathcal{U}} \setminus u$
8: $\quad$ **return** $\hat{\mathcal{U}}$

Algorithm 3 Parcel-Fit

1: **procedure** PARCEL-FIT($\mathcal{U}, \mathcal{R}$, "order", c, m)
2: $\quad \hat{\mathcal{U}} :=$ Sort($\mathcal{U}, \mathcal{R}$,"order")
3: $\quad parcels := \lceil c/m \rceil$
4: $\quad$ **for** $k := 0$ to $parcels - 1$ **do**
5: $\quad\quad$ **for** $fsu := k \cdot m + 1$ to $(k+1) \cdot m$ **do**
6: $\quad\quad\quad$ **for** all $u \in \hat{\mathcal{U}}$ **do**
7: $\quad\quad\quad\quad i_u :=$Fit($\mathcal{F}_u, r_u, fsu, (k+1) \cdot m$)
8: $\quad\quad\quad\quad$ **if** $i_u \neq 0$ **then**
9: $\quad\quad\quad\quad\quad \hat{\mathcal{U}} := \hat{\mathcal{U}} \setminus u$
10: $\quad\quad\quad$ **for** all $u \in \hat{\mathcal{U}}$ **do**
11: $\quad\quad\quad\quad i_u :=$Fit($\mathcal{F}_u, r_u, fsu, fsu + \mathcal{F}_u - 1$)
12: $\quad\quad\quad\quad$ **if** $i_u \neq 0$ **then**
13: $\quad\quad\quad\quad\quad \hat{\mathcal{U}} := \hat{\mathcal{U}} \setminus u$
14: $\quad$ **return** $\hat{\mathcal{U}}$

the criteria chosen, and later, we propose two new algorithms to solve the SA sub-problem.

1) Sorting users: As mentioned in Section I, in static operation networks, we can sort the users previous to the assignment stage since this decision influences the network performance in terms of network capacity and total fragmentation [8], [17]. Therefore, we perform different criteria to sort the network users.

This work focuses on two criteria. The first one is to sort the users according to their path length in decreasing order, i.e., from longer to shorter routes. We called this criterion as Decreasing Length (DL). On the other hand, the second one is to sort the users according to the amount of FSUs demanded to achieve communication, also, in decreasing order. We denoted this one as Decreasing Bandwidth (DB).

To represent the evaluation of the sorting procedure, we symbolically write $\hat{\mathcal{U}} :=$ Sort($\mathcal{U}, \mathcal{R}$,"order"). This procedure outputs a list of sorted users $\hat{\mathcal{U}}$ according to the "order" criteria (DB or DL).

2) Spectrum Assignment Algorithms: In this work, two algorithms, called Sliding-Fit (SF) and Parcel-Fit (PF), were developed to solve the spectrum assignment sub-problem. Both algorithms make use of the Fit algorithm to allocate a portion of the spectrum according to each user's spectral needs. The SF and PF pseudo-codes are illustrated in an algorithmic form in Algorithms 2 and 3, respectively. Both algorithms require five inputs, the network topology $\mathcal{G}$; the set of routes $\mathcal{R}$; the sorting criterion "order"; the capacity of the network links c (we consider a uniform capacity distribution, this is the capacity of all links equal to c); and the maximum bandwidth demand m (in terms of FSUs) among all network users.

For the SF algorithm (Algorithm 2), we first start sorting the users according to the "order" criterion specified. Then, we iterate through all possible FSU subsets of m consecutive slots (**line 3 to 7**). From **lines 4 to 7**, we try to assign as many user demands as possible on each iteration. Specifically, in **line 5** we evaluate the Fit sub-procedure using the selected subset of FSUs on the iteration. Next, in **line 6**, we verify if the user's demand was assigned (i.e. $i_u \neq 0$). If that is the case, the current user is discarded from $\hat{\mathcal{U}}$ in **line 7**. Finally, we return the set $\mathcal{U}$, containing the assignment results of the SF algorithm.

The PF algorithm, shown in Algorithm 3, uses the same idea of limiting the search in a subset of FSUs, although these subsets are significantly less. Following the sorting procedure (**line 2**), we split the links capacity in subsections (or parcels) in **line 3**. If the c value is a multiple of the m value, the number of parcels ($parcel$) is exactly c/m, otherwise, there would be an additional subsection of FSU with less than m FSUs.

Then, from **lines 5 to 13**, we iterate through all the parcels of FSUs computed. From **line 6 to 13** we attempt to assign as many user demands on the given FSU subsection in two steps. The first step tries to allocate all the user's demand within the limits of the parcel (**lines 6 and 7**). Next, in the second step, we again attempt to assign all the possible users on the same parcel but allowing the users to be assigned surpassing the finishing border of the parcel (**lines 10 and 11**). In both steps, if the user demands were successfully allocated (**line 8** and **12**), we subtract the assigned user from $\hat{\mathcal{U}}$. Finally, when all users have their FSUs decided, or there is no more capacity on the network to search for, we return the updated set $\mathcal{U}$ in **line 14**.

IV. Experimental Results

In this section, we evaluate our proposals' performance, comparing them with the most common approach found in the literature on the NSFNet network topology (Figure 2). The RMLSA strategies were executed on a python-based discrete event simulator, considering two possible scenarios. In the first scenario, we considered that all the network links have the same capacity (320 FSUs per link). In the second one, we assume as many FSUs per link as needed (unlimited resources). Note that, in the second scenario, the network links not necessarily will have the same capacity since it depends on the bandwidth demands on said links. For each mentioned scenario, we assign a random bitrate to each user among 10, 40, 100, 400, and 1000 Gbps using a demand generator. Remark that we used the same seed to replicate the results in different simulations. Table I translates the bitrates to FSU demands using the modulation format stage of the RMLSA strategy. However, when the communication request distance exceeds the maximum achievable range (MAR), we assigned the worst possible modulation format (BPSK). Finally, in

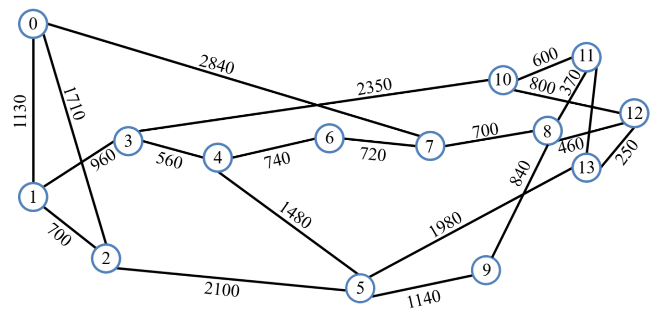


Fig. 2. NSFnet network topology with the lengths of every optical link (in km).

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Topology	NSFNet
Number of users	182
Sorting strategies	DB, DL
SA Algorithms	FF, SF, PF
Link Capacity	320, as much as needed
Bitrates	10, 40, 100, 400, 1000 Gbps
Modulation Formats	BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM
Bandwidth (FSUs)	Table I

the spectrum assignment stage, we evaluated our Sliding-Fit (SF) and Parcel-Fit (PF) and compared their performance with commonly used technique First-Fit (FF), considering two sorting criteria discussed in Section III.

We performed these simulations for different bitrates, modulation formats, link capacities, and sorting strategies. Table II summarizes the values of the relevant parameters used to perform the different simulation scenarios. Also, we compute an average of 100 simulations for each strategy to obtain representative results.

A. Performance Metrics

We use several metrics to evaluate the performance of the RMLSA strategies tested here.

1) Attended users: The attended users correspond to the number of connection requests that can be served thanks to the given SA solution. Thus, let $\mathcal{A} = \{u \in \mathcal{U} | \, \forall u \in \mathcal{U} \;\; \& \;\; i_u \neq 0\}$ be the set of attended users with cardinality $|\mathcal{A}|$. Remark that, in our second scenario, we consider an unlimited capacity, so all the users are allocated over the network to transmit. Consequently, $\mathcal{A} = \mathcal{U}$.

2) Network capacity and spectral fragmentation: The total network capacity ($\mathcal{C}_{net}$) corresponds to the amount of FSUs assigned to all the network links. This is:

$$\mathcal{C}_{net} = \sum_{\forall \ell \in \mathcal{L}} c_\ell. \qquad (1)$$

However, we can decompose this metric in terms of the attended users' capacity $\mathcal{A}$ and the non used capacity. We distinguish that the non-used FSUs exist due to two different situations. First, due to spectral fragmentation, which corresponds to the non-used FSU in the middle area of the spectrum frequency due to management disorder. Let $\mathcal{W}$ be network fragmentation composed by the sum of all the links spectral fragmentation $\mathcal{W}_\ell$, i.e.:

$$\mathcal{W} = \sum_{\forall \ell \in \mathcal{L}} \mathcal{W}_\ell. \qquad (2)$$

Second, some non-used FSUs remain on the last part of the frequency spectrum, available due to the limited capacity given to the network links. We call them free FSUs $\mathcal{C}_{free}$.

Consequently, we can decompose the total network capacity of $\mathcal{C}_{net}$ as follows:

$$\mathcal{C}_{net} = \mathcal{C}_\mathcal{A} + \mathcal{W} + \mathcal{C}_{free}. \qquad (3)$$

Remark that, on the unlimited capacity scenario, there are no free FSUs remaining ($\mathcal{C}_{free} = 0$) since the network capacity is given by the last FSU assigned to the user.

Also, we define the relative network capacity $\hat{\mathcal{C}}_\mathcal{A}$ representing the network capacity truly used to attend the users in $\mathcal{A}$ (i.e., the last FSUs used on the network links). We compute this as follows:

$$\hat{\mathcal{C}}_\mathcal{A} = \mathcal{C}_\mathcal{A} + \mathcal{W}. \qquad (4)$$

3) Spectrum efficiency: Finally, we compute the spectrum allocation efficiency (η_{SA}) as the ratio between the total capacity demanded and the relative network capacity.

$$\eta_{SA} = \frac{\mathcal{C}_\mathcal{A}}{\mathcal{C}_\mathcal{A} + \mathcal{W}} \cdot 100. \qquad (5)$$

This metric indicates the real portion of frequency spectrum demanded by the users.

B. First Scenario

As mentioned before, we analyze first the performance of strategies studied here, assuming limited capacity. We use the same capacity for all network links ($c_\ell = 320$).

The number of assigned users $|\mathcal{A}|$ is illustrated in Fig. 3 for all SA strategy. Also, we add the modulation formats used by these users. The dashed horizontal line represents all the users demanding communication, i.e., 182 users. We can see that sorting the users according to the length of their route attend more users than those sorting by the bandwidth demands. Also, the Sliding-Fit techniques (DB-SF and DL-SF) attend more users (169.08 and 168.85) than FF and PF.

Figure 4 presents the spectrum assignment results obtained by each strategy analyzed in this work. Specifically, Fig. 4a

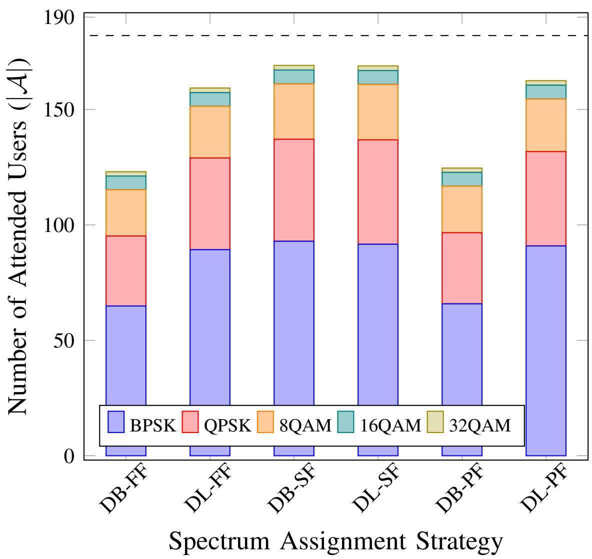


Fig. 3. Number of attended users for each strategy tested here, and the modulation formats used by these users for a the limited link capacity equal to 320 FSUs.

shows the relative network capacity $\hat{\mathcal{C}}_{\mathcal{A}}$, including all the modulation formats used on each FSU and the spectral fragmentation $\mathcal{W}$. On the other hand, Fig. 4b illustrates the spectrum allocation efficiency η_{SA}. Comparing both figures 3 and 4a, we see that the SF methods demand less network capacity (9227.7 and 8830.73 FSUs), with less spectral fragmentation (2902.03 and 2745.94) attending more users than the other strategies. Similarly, the First-Fit approach obtains worst results than PF and SF methods. On the other hand, despite the SF algorithms present less spectral fragmentation, the DL-PF strategy was the one who obtained the best relationship between the total capacity demanded and the actual required by the network to allocate it, which results in an efficiency of 70.04%.

Besides, Fig. 4a shows that strategies assigning less number of users demand the most significant amount of FSUs and present a more substantial spectral fragmentation (DB-FF and DB-PF). These algorithms tend to serve the users who demand a large amount of FSUs, affecting the spectral fragmentation due to the significant demands needed to attend them.

C. Second Scenario

Next, we compare our SF and PF algorithms with FF considering an unlimited network capacity. Note that each link capacity is unknown before the spectrum assignment stage. For this reason, we used a high number of FSUs per link allowing us to attend all network users.

Some capacity-related results obtained for this scenario are shown in Fig. 5. Figure 5a presents the relative network capacity $\hat{\mathcal{C}}_{\mathcal{A}}$ used by each studied strategy. Remark that all users were attended, then the FSUs assigned per user on each modulation format is the same in all the methods. Also, Fig. 5b shows the spectrum allocation efficiency η_{SA} of each strategy used. As shown in Fig. 5a, the DL-SF strategy has less fragmentation (4889.67 FSUs), followed by DB-SF (4896.41 FSUs) and DL-PF (4981.28 FSUs) strategies. The difference between DL-SF and DB-SF strategies is only seven fragmented FSUs (having relatively the same performance). As expected, algorithms with the least fragmentation are those who present the highest efficiency. On the other hand, the DB-FF and DB-PF algorithms presented the highest fragmentation (using almost double the required capacity).

D. Discussion

Table III summarizes the results obtained for both limited and unlimited capacity scenarios for all the RMLSA strategies considered in this work. Here, we additionally show the total amount of bandwidth $\mathcal{BW}$ (Gbps) served to the attended users $\mathcal{A}$ for each studied strategy on the limited capacity scenario. In the second scenario, both the number of assigned users and the total bandwidth transmitted are the same for all strategies. Therefore, we do not show these results since they are not relevant information for this analysis. Remark that we simulated each scenario and method 100 times each, therefore obtaining a mean value for $|\mathcal{A}|$ and $\hat{\mathcal{C}}_{\mathcal{A}}$.

For the limited capacity scenario, the main goal is to maximize some of the metrics shown in Table III. In this context, algorithms showing excellent performance according to one metric do not necessarily obtained outperform the other strategies based on a different metric.

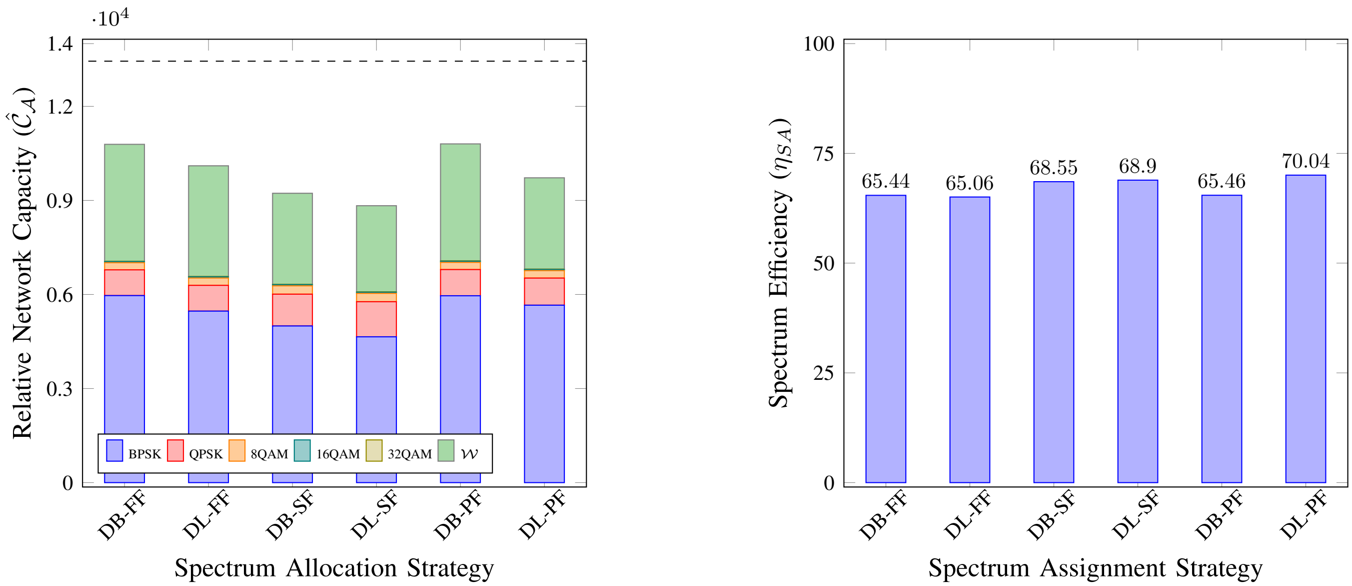
Specifically, the best performance in terms of the number of attended users was the DB-SF strategy attending 169.08 users on average. However, the DL-PF method showed the highest efficiency among all the strategies, making it the best option for cases in which the goal is to maximize the demand-capacity ratio. Finally, in terms of volume of information, the DB-PF strategy showed the highest results, serving up to 45317.8 Gbps.

In unlimited scenarios, the objective is to decrease the network's total capacity and, thus, the spectral fragmentation. In this sense, the DL-SF strategy is the best candidate since the required capacity was the least of all the strategies, showing the best efficiency.

In general, the SF algorithm's strategies obtained the best results in the metrics evaluated, presenting better indicators than the strategies based on the FF and PF algorithm. However, the selection of one or the other depends on the reader's goals.

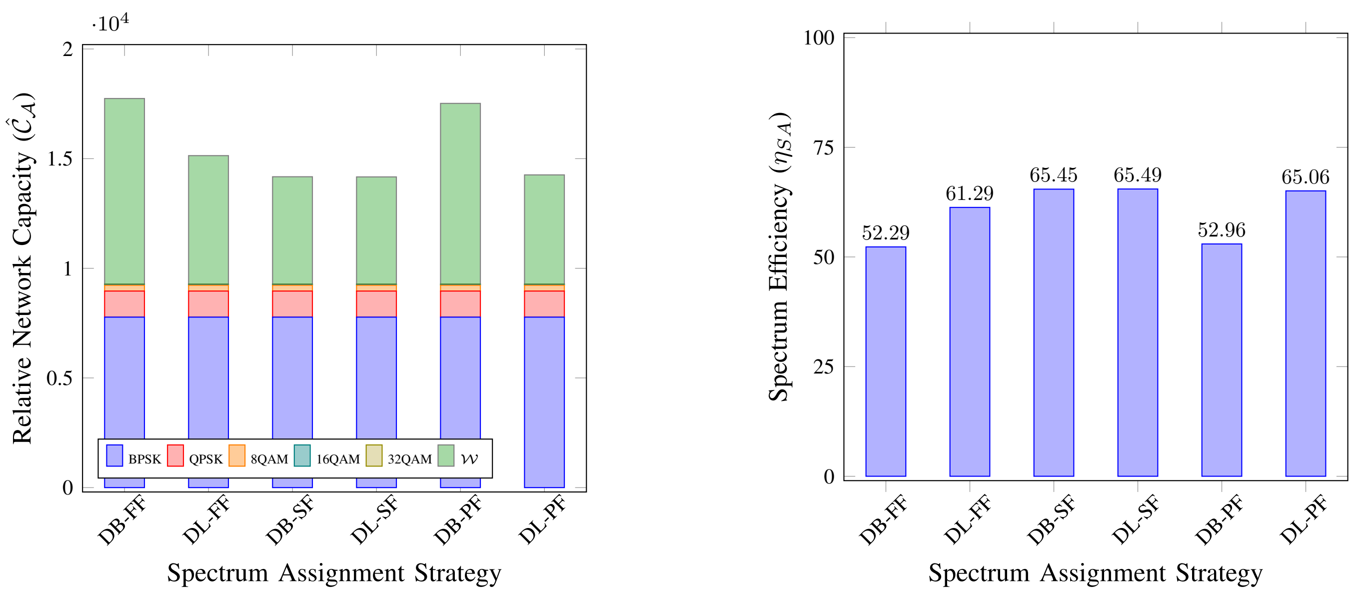
V. Conclusions

In this work, we solve the RMLSA problem for elastic optical network architectures with static network operation. To this end, we developed two algorithms, called Sliding-Fit (SF) and Parcel-Fit (PF), focusing on minimizing the spectral fragmentation. These strategies change the conventional approach of the SA solutions, searching for an available FSUs for a given user. We choose a subset of FSUs and afterward search for users to use them, and in the process, diminishing the spectral fragmentation and maximizing the attended users on the network.



(a) (b)

Fig. 4. Capacity-related results obtained by strategies tested here assuming link capacities equal to 320 FSUs. Fig. 4a shows the relative network capacity $\hat{\mathcal{C}}_{\mathcal{A}}$, as well as the modulation formats and spectral fragmentation $\mathcal{W}$. Fig. 4b shows the spectrum allocation efficiency obtained.



(a) (b)

Fig. 5. Capacity-related results obtained by strategies tested here assuming unlimited link capacities. Fig. 5a shows the relative network capacity $\hat{\mathcal{C}}_{\mathcal{A}}$, as well as the modulation formats and spectral fragmentation $\mathcal{W}$. Fig. 5b shows the spectrum allocation efficiency obtained.

We compare our solution with the commonly used method found in the literature in two different scenarios: limited and unlimited capacity. When the number of resources is limited, the reduction of fragmentation in the network allows us to attend a more significant number of connections simultaneously, increasing the total bandwidth attended. Both SF and PF outperforms the FF spectrum assignment technique. Experimental results show that the SF method obtained the best performance in terms of the number of users served. However, the highest amount of allocated bandwidth and best spectrum efficiency was obtained by PF methods.

In the unlimited capacity scenarios, to obtain less fragmentation reduces the total network capacity, leading to better spectrum allocation efficiency. In this context, the results obtained show that the SF strategy required the least capacity in the network, being the most feasible in this type of scenarios.

TABLE III
SUMMARY OF SIMULATION RESULTS

Scenario	Metric	DB-FF	DL-FF	DB-SF	DL-SF	DB-PF	DL-PF
Limited Resources	$\|\mathcal{A}\|$	123.02	159.28	169.08	168.85	124.6	162.47
	$\hat{\mathcal{C}}_{\mathcal{A}}$	10788.44	10104.13	9227.7	8830.73	10802.55	9720.71
	η_{SA}	65.44	65.06	68.55	68.9	65.46	70.04
	$\mathcal{BW}$	45103.4	40409.5	44463.6	43789.6	45317.8	42392.3
Unlimited Resources	$\hat{\mathcal{C}}_{\mathcal{A}}$	17741.16	15136.6	14173.76	14167.02	17518.55	14258.63
	η_{SA}	52.29	61.29	65.45	65.49	52.96	65.06

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